PHYSICAL PROPERTIES OF PISTACHIO NUTS

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ABSTRACT. *Physical properties of pistachio nuts were evaluated to determine distinguishable characteristics of early split pistachio nuts. The hulls of early split pistachios abnormally split open several weeks before harvest, making the kernel more vulnerable to the aflatoxin producing mold* Aspergillus flavus. *The most distinguishing features of early split pistachio nuts were found to be shell staining and hull adhesion tendencies. Using shell stain characteristics and shell dimensions, an algorithm was developed that correctly classified 90% of the early splits, and 97% of the normal nuts. When unhulled nuts were placed into a tumbler, 98% of the early split nuts kept their hulls while 95% of the normal nuts were hulled. A mechanical separation device was constructed that successfully separated 90% of the early split nuts and only 5% of the nonsplit nuts from the rest of the samples. Nut mass, length, width, and height are significantly different between early split nuts and normal nuts, however, these properties cannot be used to accurately classify the nuts into split types.* ***Keywords.*** *Pistachio nuts, Aflatoxin, Sorting, Physical properties.*

Aflatoxin is a carcinogen that may contaminate pistachio nuts prior to harvest. Nearly all preharvest aflatoxin contaminated pistachios are found in "early split" nuts (Sommer et al., 1986). The hulls of these nuts develop a split about a month before harvest, exposing the kernel to the environment and rendering it vulnerable to mold infestation that may produce aflatoxin. Early split pistachios comprise only 1 to 4% of the harvest; so, removal of this portion of the crop could be an economically sound method for eliminating aflatoxin from the pistachio commodity.

Aflatoxin is a secondary metabolite of the mold, *Aspergillus flavus*; it is known to infest several commodities such as corn, rice, soybeans, peanuts, pecans, cotton seed, and pistachio nuts (Ciegler, 1975). Aflatoxin is a toxic and carcinogenic substance that has been known to cause deaths in farm animals that consumed heavily contaminated feed (Farsaie et al., 1981). Aflatoxin caused hepatitis and death in more than 100 people who consumed severely contaminated maize (Samarajeewa et al., 1990); however, it is not common to find food contaminated with aflatoxin to the degree that it will cause immediate health problems. Aflatoxin has been traced to increased chances of liver cancer after repeated consumption of low levels (above 20 ppb) of contaminated food (Samarajeewa et al., 1990). Dichter (1984) estimated that due to aflatoxin exposure in the United States, 58 to 158 people per year are inflicted with liver cancer. However, Yeh (1989) reported that in southeast China where food regularly contains high aflatoxin concentrations, 91% of the liver cancer deaths in this area were also people who tested positive for hepatitis B1.

Pistachio nuts are characterized by a split in the shell at the calyx end of the nut. This split normally occurs on the tree about a month before harvest. The hull (mesocarp) of the pistachio usually encloses the shell and remains intact through harvest, serving as protection for the kernel. On normal nuts, there is space between the hull interior and shell exterior, so the shell can split open without splitting the hull. However, about 1 to 4% of the time, the hull will adhere tightly to the shell and the hull will split open along with the shell. These nuts are called "early splits". The split in the hull allows an unobstructed passage to the kernel for airborne mold spores and insects or other small animals, such as mites, that might be carrying mold spores (Sommer et al., 1986). Insects and small animal infestation rates on early split nuts are much higher because of the easy access to the kernel. The mold, *Aspergillus flavus*, has been found in pistachio nuts before harvest (Thomson et al., 1978). Sommer et al. (1986) and Thomson et al. showed that nearly all the *Aspergillus flavus* contaminated nuts also have split, insect damaged, or bird damaged hulls before harvest. Sommer et al. found the incidence of aflatoxin contamination to be about 50 times greater in early split nuts than in normal nuts (1 in 500 for early split nuts versus about 1 in 25,000 of all nuts). The aflatoxin contaminated normal nuts studied by Sommer et al. were found to be contaminated at the lowest levels of detectability (less than 2.0 ppb) while many early split nuts were found to contain aflatoxin concentrations greater than 20 ppb and some above 1,000 ppb.

The prominent physical characteristic of an early split pistachio is a distinct, dark and smooth-edged split on the suture of the hull (fig. 1). When an early split occurs, the split will normally start at the calyx end of the hull and be present on only one side of the nut. Early split nuts whose hull splits 60 to 20 days before harvest have a much greater

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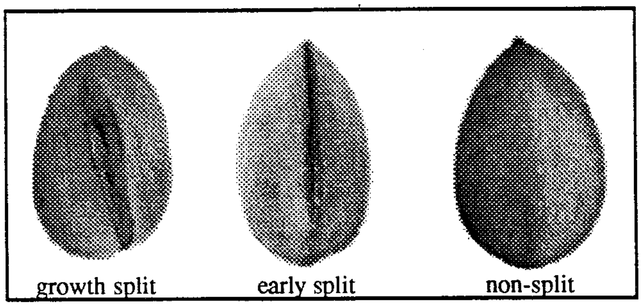

Figure 1–Illustration of the three pistachio hull split types.

opportunity for *Aspergillus flavus* infestation and high levels of aflatoxin, since the mold has had a much longer time to grow and excrete aflatoxin. These nuts, with the split in their hull, tend to be drier than normal nuts or other nuts whose hull split closer to harvest. Doster et al. (1991) found that early split nuts with dry, shriveled hulls were three times more likely to be infested with *Aspergillus flavus* than early split nuts with green, nonshriveled hulls. Furthermore, aflatoxin was found in 31% of the dry, shriveled early split nuts at an average concentration of 31 ppb and aflatoxin was seen in only 6% of the nonshriveled appearing early split nuts at an average concentration of 0.4 ppb (Doster et al., 1993).

Another kind of split that can occur on a pistachio hull shortly (less than 15 days) before harvest is called a growth split. Growth splits on pistachio hulls are characterized by ragged brown edges, and the split is randomly oriented and much wider than an early split (fig. 1). It has been shown that these nuts do not contain aflatoxin or *Aspergillus flavus* at harvest time, presumably because the mold has not had time to develop (Sommer et al., 1986). For the purposes of this study, growth split nuts are not considered a health risk and are classified as normal nuts along with nonsplit nuts. However, because of their morphological differences, their physical properties are discussed separately.

As stated earlier, *Aspergillus flavus* is also prevalent in bird and insect damaged nuts. These nuts often have abnormally low densities and are removed in a normal pistachio processing plant with existing quality control equipment (Kader et al., 1980). Therefore, bird-damaged and insect-damaged nuts were not included in this study. The nondamaged early split nut densities are indistinguishable from normal nuts so they are not removed during normal processing.

The commercial practice to screen most nuts (pecans, peanuts, etc.) for aflatoxin is to remove stained, blemished, or insect-damaged nuts with color sorters. Stoloff (1980) estimates that 66% of the aflatoxin contaminated peanuts are removed by standard sorting and processing practices. *Aspergillus flavus* also excretes kojic acid which, after reaction with kernel tissue, is fluorescent under ultraviolet illumination. This property has been used to develop sorting devices for other commodities. For example, Tyson et al. (1974) developed a sorter for pecans using this property. Pelletier et al. (1991) developed a high speed peanut sorter that examines individual peanuts for fluorescence at a rate of 360/min. Farsaie et al. (1981) and McClure et al. (1980) developed an automatic sorter for contaminated pistachio nuts. However, it has not yet been shown that there is a direct correlation between aflatoxin content and florescence in pistachio nuts. Thus, these machines are not currently utilized commercially.

OBJECTIVES

The objective of this study is to quantify the physical properties of normal nonsplit, early split, and growth split pistachio nuts, and to investigate methods for separating early split pistachio nuts using physical characteristics. The properties that were investigated are listed in table 1. The goal of this project is to determine if any of the investigated properties or combination of properties can be used to separate early split pistachios from normal nuts.

METHODS AND MATERIALS

Pistachio nuts were collected at three different orchards near Madera, California, during commercial harvest. Each of the orchards was harvested on a different date, with the first orchard harvested at the beginning (4 September 1992), the second orchard in the middle (22 September 1992), and the third orchard late (30 September 1992) in the harvest season. The trees in all three pistachio orchards were of the 'Kerman' cultivar. Nuts were collected by walking down random rows in the orchard and searching all sides of each tree for early and growth split nuts. Nonsplit nuts were also collected randomly from trees while searching for early and growth split nuts. No ladders were used so all nuts collected from trees were no higher than 3 m above ground. There did not appear to be any spatial pattern of occurrence of early split nuts. The quantity of early split nuts varied from tree to tree and orchard to orchard. Many trees had no early split nuts while some trees had as many as a dozen. There did not appear to be a tendency for early split nuts to occur on a particular location on the tree, i.e. north, south, east, or west or height on the tree. Nor, did there appear to be a tendency for early split nuts to occur on a shaded florescence versus a florescence receiving unblocked sunshine. These observations are consistent with Sommer et al. (1986). Nut samples were also taken from the harvester bins. Nuts were scooped out of the harvester bins and sorted by hand into split-type groups. About 30% of the samples were from harvester bins and the remaining 70% were collected directly from the trees.

Table 1. Investigated properties of pistachio nuts

Unhulled Nuts	Hulled Nuts
Length	Length
Width	Width
Height	Height
Mass	Mass
Volume	Hull moisture content
Density	Shell & kernel moisture content
Moisture content	Hull thickness
Terminal velocity	Hull friction factor (hull still on nut)
Hull split length*	Width of split in shell
Hull split width*	Distance from hull to kernel
Mass center	Shell color (dried nuts)
Hull adhesion	
Needle insertion into hull	

* Early splits only.

Pistachio trees have a biennial production cycle. They produce a high yield one year and a moderate yield the next. The year of this study (1992) was a high bearing year for pistachio trees sampled.

During collection, nuts were placed in bulk in large polyethylene bags and kept cool in an ice chest until the sample collection was completed for the day (no more than 4 h). After all the nuts were collected, each nut was placed in 5.08 × 7.62 cm (2 × 3 in.) zipper sealed polyethylene pouches, then placed back in the large polyethylene bag in the ice chest. Upon returning to the laboratory after each harvest, 60 nuts of each split type group (early split, non-split, and growth split) were randomly selected for physical property measurement. Nuts with shriveled appearing hulls and very small nuts (less than 10 mm in length) were not included in these tests. If one of these nuts was selected, it was set aside and a replacement was selected. Next, wet mass was measured on the 60 selected nuts from each split-type group. The nuts were returned to their individual zipper locked pouches and placed in a refrigerator kept at 4° C overnight and between all subsequent tests.

The mass of each nut was measured on an electronic scale (Sartonius, A200S). The length, width, and height of each nut was measured with digital electronic vernier calipers (Mitutyo, 500-351). The length was defined as the distance from the calyx end to the stem (fig. 2). These measurements were made on all of the selected unhulled nuts. The nuts were then equally divided into two groups for further measurements. One group would remain unhulled and the other would be hulled. The nuts in the unhulled group were used to measure mass center, density, and unhulled nut moisture content. Nuts in the hulled group were used to measure hull friction factor, length, and width of the hull split (early splits only), hull thickness, hull moisture content, and hulled-nut moisture content.

The hull friction factor was measured using a V-shaped, polished, stainless steel inclined trough apparatus. The nut was placed in the trough and the trough was inclined until the nut started to slide. The angle of inclination of the trough with the horizontal was recorded and the coefficient of static friction factor was calculated using the trough angle. The length of the hull split (early splits only) was measured using a ruler. The split region of the nut was rolled over the ruler to measure the "flat" transposed length of the split. The width of the hull split was measured at its widest point with digital electronic calipers. The nuts were hulled by hand and the wet hull mass and wet hulled-nut mass (shell and kernel mass) were measured within minutes after hulling, before any drying could take place.

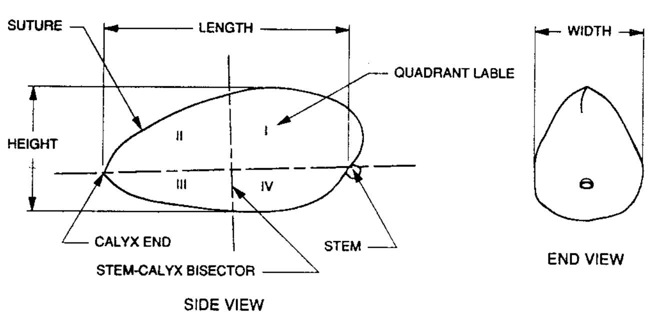

Figure 2–Schematic drawing of nut dimensions.

The shell length, width, height, and hull thickness were measured with digital electronic calipers. The hull thickness measurement was taken with electronic calipers at the calyx tip.

With the dimensional measurements complete, the hulls and hulled nuts were placed in individual aluminum dishes for drying. Drying was performed in a forced draft oven (Precision Scientific, model 18) at 100° C for 12 h, then the nuts were removed for mass measurement, and returned to the oven. Four hours later, the nuts were removed and the mass was measured again. This process was repeated until there was less than 1% change in mass from the previous measurement. For all of the experiments, the nuts consistently dried in 20 h. The moisture content of the nuts and hulls was calculated on a wet basis.

The mass center in the suture plane of unhulled nuts was approximated by hanging the nut from a needle inserted underneath the hull skin at a point on the suture. The nut was fastened loosely enough to the needle so it could easily pivot on the needle point. With the nut still on the needle, a vertical line was drawn on the nut down from the needle point. This was repeated using another point on the suture with the nut rotated approximately 90° from the previous test. The intersection of the lines approximates the mass center location in the suture plane. The nut was divided into four quadrants bordered by a line from the calyx tip to the stem intersected at its midpoint by a normal line. The quadrant (labeled "side view" in fig. 2) containing the mass center and the distance from the calyx-stem line midpoint were recorded.

The volume and density of the unhulled nuts were measured using the pycnometer method (Mohsenin, 1986). This procedure was performed with toluene, a specific gravity flask (Fisher Scientific, 1620-25) and an electronic scale. The density of the nut was calculated from the wet mass of the nut divided by its volume.

The moisture content of individual unhulled nuts was measured using the same protocol as that performed with the hulls and hulled nuts. The unhulled nuts also dried to a constant mass after 20 h. The difference in mass from the day of collection was used to calculate the moisture content on a wet basis.

The terminal velocity of unhulled nuts was measured by dropping individual nuts from a 6.62 m (21.7 ft) height and recording drop times. Nuts were dropped from a photo sensor (Keyance, PG-602) onto a plate instrumented with an accelerometer (Dytran, 3100A1). The time between the signals from the photo sensor and accelerometer were measured with a digital oscilloscope (Tektronix, 2430A). Using the measured drop distance and drop time, the terminal velocity was determined by iterative application of equation 1, below (Mohsenin, 1986):

$$s = \frac{V_t^2}{g} \ln\left[\cosh\left(\frac{g}{V_t}t\right)\right] \tag{1}$$

where

s = distance of drop (m)
g = gravitational acceleration (9.81 m/s^2)
V_t = terminal velocity (m/s)
t = drop time (s)

The distance from hull exterior to the kernel was measured at the calyx end of the nut. The nut was supported on end with the calyx end pointing up, and the height was measured with a micrometer (Starrett, 445). The hull at the calyx end was then peeled away, and the height to the tip of the kernel was measured. The difference between the two measured heights is the distance from the hull to kernel.

The shell color was measured both quantitatively and qualitatively. Early split nuts tend to have a dark brown stain on their shells along the perimeter of the split. They also tend to have a more yellowish hue all over their shell. The dried nuts from the moisture content tests were examined for a dark brown stain adjacent to the shell split or anywhere on the shell or for yellowish shell hue covering at least 90% of the shell surface. An estimate of the percent coverage of a dark brown or black stain on the shell was also noted. A stain was defined as any dark brown or black discoloration of at least 2 mm in diameter. Along with these observations, the length, width, and height of the dried nuts were measured. Also, the shell color was measured with a tristimulus colorimeter (Hunter Lab, 025-A) on a 3-mm-diameter spot at the apex of the shell split. This point often had a portion of the characteristic early split stain, but not always.

The hull adhesion to the shell was quantified by placing 30 nuts of a particular split type in a tumbler rotating at 43 rpm. The tumbler body was constructed from a 40-cm-diameter PVC pipe and lined with eighteen 1.75-cm steel angle irons for vanes (fig. 3). The tumbler was stopped every 30 s and the quantity of nuts that had been separated from their hulls was recorded. This was repeated until all of the nuts became separated from their hulls.

Another mechanical separation method consisted of a stationary roller and a rotating roller with needles emanating from its surface (fig. 4). The principle of this method is that the needles on the roller will enter the split in the hull of an early split nut and carry it out while non-split nuts would have no crevice for a needle to enter and remove the nut. Thirty nuts of each split type were placed on the rollers and its removal or retention was noted.

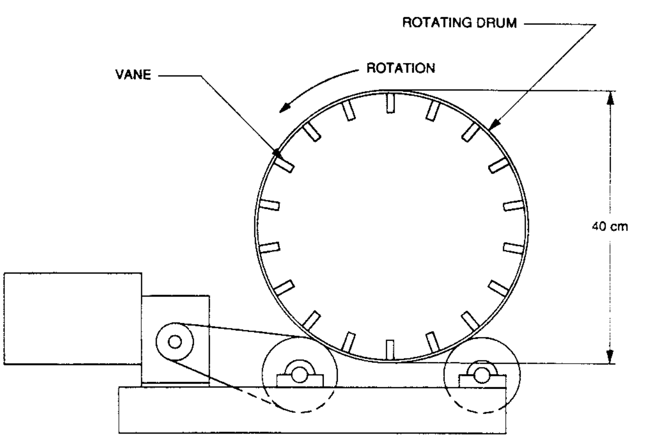

Figure 3–Schematic drawing of the tumbler used to evaluate pistachio hull adhesion.

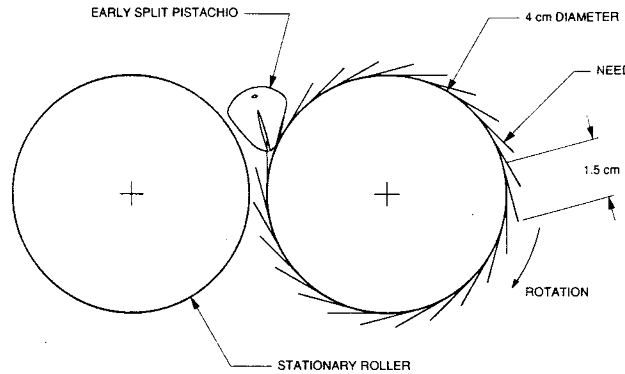

Figure 4–Schematic drawing of the roller and needle mechanical separator.

RESULTS AND DISCUSSION

Twenty percent of the tested nonsplit and 9% of the growth split nuts were found to have unsplit shells and undeveloped kernels. This type of nut is removed in pistachio processing plants. To avoid bias to the normal nut data, the measurements from these undeveloped nuts were removed from further analysis.

The first step in analyzing the data was to determine if the mean for a given property was significantly different for early splits than nonsplit and growth split nuts. This was performed with Fisher's least significant difference test with $\alpha = 0.05$. Listed in table 2 are the means, minimum, maximum, coefficient of variance (CV), sample size, and significance for the pistachio properties studied. The hull adhesion and needle separator tests were not included in this analysis.

Discriminant Analysis (SAS, 1989) was then used to evaluate the feasibility of using individual or multiple pistachio properties to differentiate early split nuts from the other nut types. Pistachio nut properties listed in table 2 that were not significantly different between early split and normal categories were not included in the classification study.

Discriminate models could only be made using properties of either hulled nuts or unhulled nuts as these two groups of tests used different samples. The bulk hulling and handling processes in current practice at pistachio processing plants in California cannot keep track of a nut through the huller. Thus, a model using both hulled and unhulled properties would have little practical value. The best models found for classifying nuts by split type for hulled and unhulled nuts are listed in table 3. The total nuts correctly classified was calculated by weighting the early split classification by 4%, the nonsplit nuts by 76%, and the growth split nut classifications at 20%. For unhulled nuts, the product of mass and volume classified nuts into the correct split types with the fewest early split errors. However, measuring both volume and mass for an individual nut at a high throughput rate is not an immediately feasible commercial practice.

It is desirable to use properties of hulled nuts to separate early splits since hulled nuts pass through the processing plant at a slower rate than unhulled nuts. Unhulled nuts are delivered to the plant, hulled within a few hours, then dried and stored. The hulled nuts are taken from storage and processed throughout the year while unhulled nuts are all

Table 2. Statistics of investigated pistachio properties

Property	Early Split Nuts					Nonsplit Nuts					Growth Split Nuts					Sig. Diff. Means†
	Mean	Min	Max	CV (%)	n*	Mean	Min	Max	CV (%)	n*	Mean	Min	Max	CV (%)	n*	
Unhulled nuts:																
Hull friction factor	0.39	0.22	0.59	18.50	180	0.34	0.18	0.49	31.91	143	0.40	0.32	0.47	9.57	173	no
Hull thickness (mm)	1.31	0.25	2.60	29.85	180	1.82	0.41	2.77	25.39	143	1.62	0.27	2.21	22.79	173	yes
Height (mm)	16.49	12.33	20.67	9.17	180	18.51	15.55	23.07	7.89	143	17.05	12.53	20.35	9.43	173	yes
Length (mm)	21.56	13.55	26.31	6.45	180	24.22	20.66	28.35	5.87	143	21.93	14.35	26.27	8.34	173	yes
Width (mm)	15.08	11.22	21.92	8.99	180	16.75	14.32	20.25	7.49	143	17.05	12.63	23.52	11.32	173	yes
Mass (g)	2.72	1.26	4.43	21.75	180	3.62	1.80	5.58	19.20	143	3.22	1.99	4.65	18.78	173	yes
Volume (mL)	2.60	1.21	3.83	21.58	180	3.82	2.50	5.35	16.76	143	3.13	1.94	4.50	22.32	173	yes
Density (g/mL)	1.03	0.88	1.28	6.51	180	0.93	0.68	1.11	12.03	143	1.03	0.88	1.33	4.32	173	no
Moisture (% w.b.)	45	9	60	25	180	54	38	70	10	143	48	16	69	19	173	no
Hull split length (mm)	26.71	15.00	60.00	29.85	180	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a		n/a
Hull split width (mm)	1.10	0.10	3.50	76.21	180	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a		n/a
Terminal velocity (m/s)	11.69	9.92	13.12	5.95	90	12.47	10.77	14.55	7.93	90	11.54	10.11	13.42	0.91	90	no
Mass center‡, radius (mm)	3.80	1.00	7.00	37.18	90	3.80	1.00	7.00	41.84	90	n/a	n/a	n/a	n/a		no
Hulled Nuts:																
Hull moisture (% w.b.)	77	57	83	7	90	79	66	90	6	52	76	54	85	8	83	no
Moisture (% w.b.)	41	26	84	45	90	37	29	43	10	52	34	25	43	12	83	no
Height (mm)	14.60	10.75	18.69	8.71	90	15.99	13.74	18.92	7.33	52	15.06	12.43	18.00	8.15	83	yes
Length (mm)	19.31	14.89	22.48	7.91	90	20.63	13.46	24.16	7.73	52	19.85	15.77	22.95	6.62	83	yes
Width (mm)	12.77	10.10	14.76	6.98	90	14.21	12.35	16.03	5.63	52	13.50	11.14	15.86	7.22	83	yes
Shell split width (mm)	1.01	0.21	3.32	75.14	90	2.52	0.25	6.05	47.93	52	2.48	0.41	5.32	39.56	83	yes
Mass (g)	1.85	0.81	2.64	18.06	90	2.41	1.72	3.16	12.25	52	2.11	1.26	4.10	19.42	83	yes
Shell color§ (x value)	0.403	0.349	0.444	4.30	83	0.364	0.339	0.396	3.36	88	0.373	0.343	0.426	4.80	53	yes
Shell color§ (y value)	0.381	0.349	0.407	2.87	83	0.362	0.334	0.383	2.46	88	0.371	0.332	0.408	3.70	53	yes

* n is the sample size (total for all three harvests).
† Early split means significantly different from nonsplit and growth split means at the 5% level.
‡ Seventy seven percent of the mass centers on early split nuts fell in quadrant 1, 19% in quadrant 2, and 4% in quadrant 4. Eighty-four percent of the mass centers on nonsplit nuts fell in quadrant 1, 11% in quadrant 2, and 5% in quadrant 4. Growth split nuts were not evaluated in this experiment.
§ Chromaticity values are normalized.

handled during the four- to six-week-long harvest season. It is highly unlikely that any *Aspergillus* molds that existed on an incoming nut would spread in properly maintained dry storage bins. Mojtahedi et al. (1978) showed that Iranian pistachios inoculated with *Aspergillus flavus* would not become contaminated with aflatoxin if stored below 25% relative humidity. Similar results have been shown for barley (Chang et al., 1981).

Table 3. Classification of pistachio nuts using hulled and unhulled nut properties

Classification Model	Nuts Correctly Classified (%)			
	Early Split	Non-Split	Growth Split	Total*
Hulled nuts:				
Shell color	81.8	96.2	84.3	93.2
Length, width, shell split width	74.4	77.8	82.2	78.5
Length, width, height, shell split width	74.4	76.7	80.0	77.3
Length, height, shell split width	74.4	74.6	80.0	75.7
Length, width, height	62.2	80.0	70.0	77.3
Length, width, height, mass	61.1	92.2	73.3	87.2
Unhulled nuts:				
Mass × volume	92.2	74.4	65.6	73.4
Length, width, height, mass, volume	90.0	87.8	54.4	81.2
Mass, volume	90.0	82.2	57.8	77.6
Length, width, height, mass × volume	82.2	91.1	70.0	86.5
Length, width, height, mass	82.2	84.4	56.1	78.7
Length, width, height, volume	81.1	88.9	70.0	84.8
mass	78.9	71.7	63.3	70.3
Length, width, height	77.2	87.8	59.6	81.7
Length, height	70.6	86.7	62.8	81.3
Length, width	70.0	86.7	62.6	81.2
Volume	64.4	95.5	64.4	88.0
Density	21.1	95.6	83.3	90.2

* The total nuts correctly classified is calculated by weighting the early split classification by 4%, the nonsplit classification by 76%, and the growth split classification by 20%.

Examining table 3, we find that shell color is the most distinguishable characteristic of hulled early split pistachio nuts. This classification is based on the chromaticity of the tristimulus color reading results. Inspecting the hulled nuts after the moisture content tests, 75% of early split nuts, 7% of growth split nuts, and 0% of the nonsplit nuts had stains adjacent to the split edge. Also, 45% of early split, 4% of growth split, and 2% of nonsplit nuts had a yellowish hue over at least 90% of their shells. Doster et al. (1993) also observed that early split pistachio nuts have stains near the perimeter of the shell split. Furthermore, Doster reports that early split nuts with shell staining had a higher incidence of *Aspergillus* molds than nonstained early split nuts.

Using both the categorical shell stain data (stain on split perimeter or no stain, and yellowish hue or not) and the dimensions of the hulled and dried pistachios, nuts were classified into the split types. If a nut had a stain adjacent to the shell split, or had a yellowish hue, or if the product of its length and width was less than 230 mm^2, then it was classified as an early split. This criteria correctly classified 90% of the early split, 97% of the nonsplit, and 76% of the growth split nuts. Other models using all of the dimensions were evaluated, but no improvement in classification accuracy was found.

The extent of staining on a shell does not appear to give an indication of its split type. The introduction of the percent stain coverage data into a sorting criteria reduces the sorting accuracy rather than enhancing it. However, nonsplit nuts tend to be more heavily stained on the stem end while early split nuts tend to have more staining in the middle of the nut shell. If the hulled nuts were to be inspected with a computer vision system, this criteria could be helpful along with the other classifying criteria previously discussed.

The hull adhesion tests produced positive results. The growth split nuts required the shortest time to become separated from their hulls and nonsplit nuts required slightly more time. Ninety-five percent of the growth split and nonsplit nuts became separated from their hulls in 3 and 3 1/2 min, respectfully. The early split nuts required 6 min for 95% of their hulls to become separated from their shells while only 2% of the early split nuts lost their hulls before 3 1/2 min. These results indicate that hull adhesion may be a viable classification technique. However, further study is needed to fully evaluate the classification accuracy of this method.

The roller and needle device successfully removed 90% of the early split nuts and only 5% of the nonsplit nuts. However, the roller also removed 95% of the growth split nuts. This device could be useful as a quick presorter in front of a more time intensive sorter such as a computer vision system. With the mechanical presorter, most non-split nuts will not have to pass through the secondary sorting equipment.

Shriveled early split nuts were not examined in this study. Based on Doster's (1991) findings that shriveled early splits contain higher incidences and higher concentrations of aflatoxin, these nuts should be examined carefully. The shriveled nuts' low moisture might be detected with near infrared spectroscopy. Also differences in hull color and density could possibly be used as a sorting criteria for these nuts. However, it is not known at this time how thoroughly aflatoxin-contaminated nuts will be removed by only sorting shriveled nuts. This study showed that most nonshriveled early split nuts have unhulled nut moisture contents comparable to nonsplit nuts.

Conclusion

Shell color is a promising property to use as a criteria for sorting early split nuts. Pistachio nuts are currently examined by color sorters in commercial processing plants. It is likely that the existing color sorters remove most of the stained early split nuts. However, the color sorted nuts are often re-examined and a portion returned into the processing cycle. Before this is done, early split nuts should be removed by detecting properties specific to early split nuts such as stains on the shell split perimeter, length and width product (or cross-sectional area), yellowish hue on shell, or dominant stain location. Additional research is needed to investigate detection of these properties using color sorters or computer vision.

Hull adhesion to the shell is another promising physical property that could be taken advantage of to separate early split nuts from normal nuts. This process could conceivably be done in bulk rather than examining individual nuts as would be necessary with the color sorting method.

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